

Evaluation of Keyway Grout Test Methods for Precast Concrete Bridges

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Precast, prestressed concrete box beams, bulb tees, and voided slabs are used in short-to-medium span bridges. These bridge elements have grouted keyway sections to transfer the vertical shear forces between adjacent elements. The keyways are filled with differing types of non-shrink grouts. By definition, these non-shrink grouts do not have requirements for maximum shrinkage limits or minimum bond strength. Both properties are critical for effective load transfer. In the field, leaking keyways and vertical faulting of keyways have been reported. A laboratory study was undertaken to compare component material tests and composite grouted keyway specimens using two different grouting materials: non-shrink grouts and magnesium ammonium phosphate mortars. Comparative composite specimens were tested in vertical shear, longitudinal shear, and direct tension. Results indicate significant differences in performance between the materials. Composite testing of the grouted keyway assemblies, rather than component materials testing, was shown to be a more accurate way to evaluate the performance of the grouting material.



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Many state Departments of Transportation (DOTs) and county bridge jurisdictions have made efficient use of precast, prestressed concrete box beams. Several factors appeal to the agencies using this system:

1. Fast installation
2. In-plant quality control, enabling production of highly durable, low water-cement ratio concrete
3. Considerable shrinkage developed prior to shipment due to in-plant steam curing and cataloging, allowing drying shrinkage to occur prior to erection

These bridge systems are favorable in short-to-medium span simple structures employing either composite or non-composite design.

To provide load transfer from one adjacent element to another, the keyway is grouted with one of several different grouting materials, including non-shrink grouts or high cement factor, truck-mixed mortars. To aid in the control of member alignment, transverse post-tensioning or transverse, high strength threaded rods are tensioned to induce transverse compression in the concrete system across the width of the bridge. Because the spacing of the transverse tensioning steel typically ranges from 20 to 40 ft (6.1 to 12.2 m), much of the force can be dissipated between the stressing locations and becomes ineffective in producing a uniform compression in the members across the deck. Alternately, the keyway is grouted first and the members are then transversely stressed.

After transverse stressing and subsequent grouting, the deck surface is often coated with a waterproofing membrane and later overlaid with an asphaltic wear course (see Fig. 1). Alternately, the membrane is eliminated and a composite action concrete wear course is placed instead. This system is quick and simple to install and allows easy replacement of old bridges or upgrading for higher load capacity standards or wider lanes.

PROBLEM DEFINED

It has been brought to our attention by two regional Precast/Prestressed Concrete Institute associations that, on occasion, problems occur with precast,

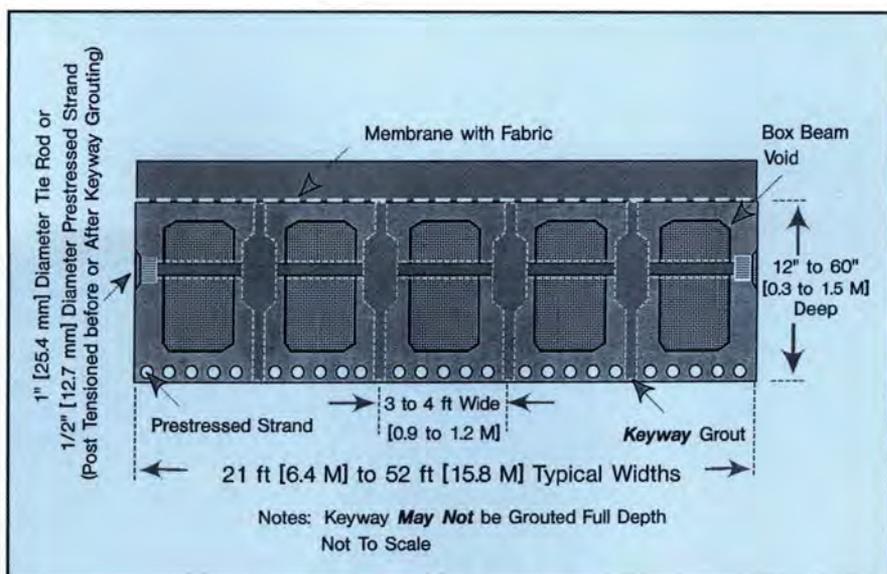


Fig. 1. Typical precast concrete box beam bridge section with asphaltic or concrete wear course installed.

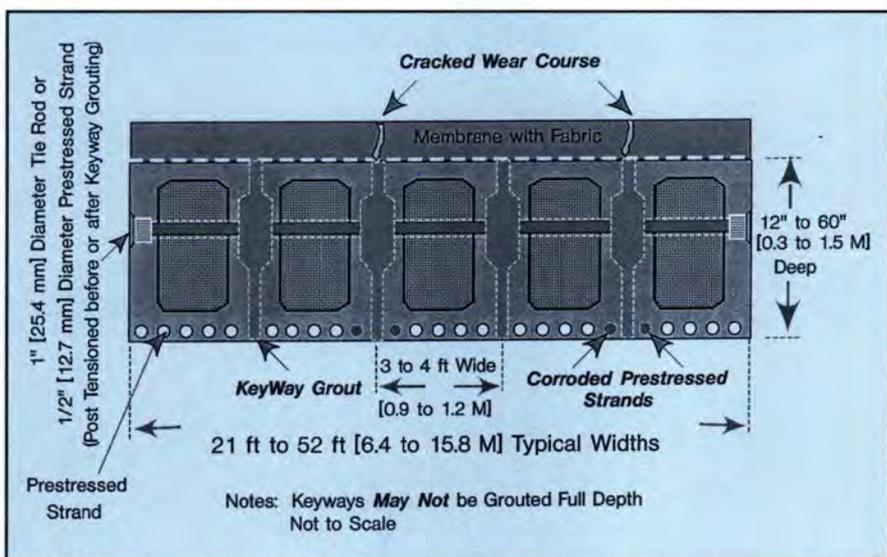


Fig. 2. Typical precast concrete box beam bridge deck section with asphaltic or concrete wear course after significant traffic exposure.

prestressed concrete box beam construction. Sometimes, the grout in the keyway allows leakage that is discovered during inspection of the underside of the precast concrete elements. This is indicated by a white efflorescence adjacent to the grouted keyway

These leaking keyways can carry chloride-laden road salts or sea sprays to the underside of the box beams, voided slabs, and bulb tees. Capillary action wicks these salts into the precast concrete, leading, at times, to corrosion of the tie bars and bottom strands adjacent to the joints (see Fig. 2). Shrinkage and loss of bond with the keyway

vertical face allow initial shear displacement [up to 0.02 in. (0.5 mm)] to develop with continuing fatigue, causing the failure and deterioration of the keyway.¹ This provides the mechanism to over-stress the membrane as it becomes brittle in cold weather. The more rigid membrane becomes torn, losing effectiveness as a waterproofing material.

An indication of imminent problems is the development of longitudinal cracks in the wear course spaced typically above grouted keyways in the wheel paths (see Fig. 3). These cracks occur principally in the righthand lane but can develop in both lanes on a

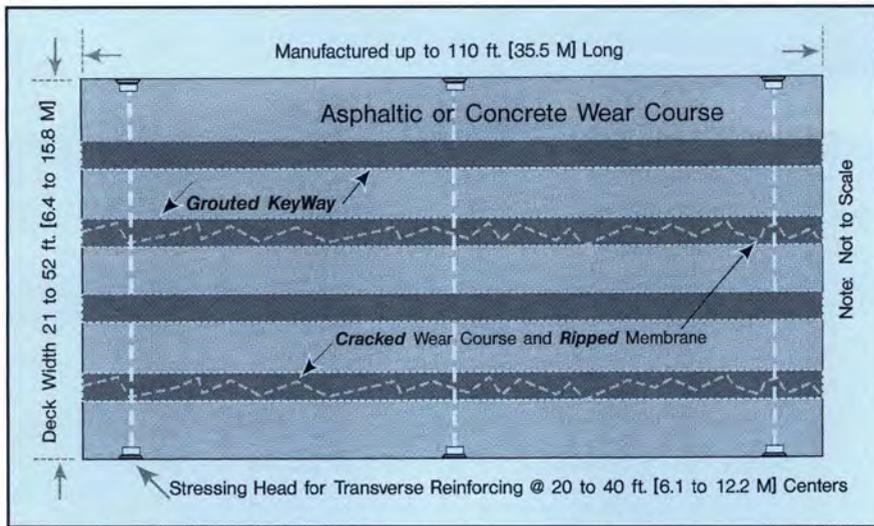


Fig. 3. Top view of keyway grouted precast concrete box beam overlay after significant exposure.



Fig. 4. Corroded prestressed strands on both sides of grouted keyway on bottom side of box beam bridge. Note staining on member.



Fig. 5. Midspan replacement of box beam bridge. Arrows show replaced midspan box beams, deck, and hanging broken prestressed tendon from box beam.

split lane bridge. Both asphaltic and concrete wear course bridge surfaces may display this type of cracking.

During inspection after bridge topping and box beam elements have been removed, there have been several instances of the grout falling out of the formed keyway. Occasionally, corroded strands have been observed on both sides of the keyway on the bottom of these box beam elements with lengths of 6 to 10 ft (1.83 to 3.05 m) (see Fig. 4).² Some of these strands have concrete adhering to them. Loss of capacity and serviceability ensues.

Strict control is placed on the precast concrete element. Post-tensioning transverse strands or high strength transverse threaded rods with nuts and plates are carefully spaced and stressed to provide compression across the elements. Unfortunately, the grout is often given second-class treatment for its intended purpose — effective long term vertical shear transfer between adjacent members. Therefore, the grout becomes the weak link in the system.

SIGNIFICANCE OF RESEARCH

This keyway failure poses a significant maintenance problem to the bridge engineer, who now must have the wear course removed, the distressed box beams replaced, and the keyway grout replaced (see Fig. 5), or the underside of a prestressed concrete member repaired. Often, a slight improvement is made in the design of the shear keyway itself, but little evaluation has been made of the grouting systems. This study attempts to evaluate keyway grouts from a different perspective in order to eliminate these costly serviceability and repair problems.

OBJECTIVE OF THE TEST PROGRAM

As a result of these reported problems, a laboratory investigation of the keyway grout problem was initiated. A written inquiry requested submission of materials for keyway grout consideration with the properties listed below:

- Cementitious grout with non-shrink properties

- Polymer modified preference
- Minimum placement temperature of 40°F (4.4°C) and greater
- Non-metallic
- Free-flowing
- Minimum strength of 6000 psi (41.3 MPa)
- Bond strength with 100 percent in substrate failure

PRELIMINARY EVALUATION

Most DOTs and bridge agencies specify either plant ready mixed, high cement factor cement:sand mortar with a job-site added prehardening expansive system containing a gassing agent or prepackaged non-shrink grouts that expand after hardening. These materials are used because they are considered non-shrink. An expansive mechanism is developed in the mortar to produce the non-shrink properties. A close review of the specifications and the type of performance testing required reveals that these types of grouts raise general concerns for the following reasons:

1. Non-shrink grouts are covered under ASTM C 1107 Specification³ (see Table 1), which establishes strength, consistency, and expansion criteria. The physical properties of these grouts are listed in Table 1 of that specification (not published herein) for:
 - ASTM C 942 using 2 in. (50.8 mm) restrained cube compressive strength⁴ (see Table 2)
 - Consistency (see Table 3)
 - Vertical height change (see Table 4)
 Minimum and maximum requirements are listed in this specification.

This specification lists three types of grout depending on their volume change characteristics: prehardening volume controlled types; post hardening volume controlled types; and combined volume controlled types. Workability of these grouts is defined by their consistency classification using the ASTM C 230 Flow Table⁵ or the ASTM C 939 Flow Cone.⁶

The prehardening height change requirements are measured by ASTM C 827,⁷ the “Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens for Cementitious Mixtures.” The post hardening

requirements are performed according to ASTM C 1090,⁸ “Test Method for Measuring Height Changes of Cylindrical Specimens from Hydraulic Cement Grouts.” These test methods rely on vertical height changes of 3 x 6 in. (76.2 x 152.4 mm) cylindrical specimens. The tests do not measure longitudinal drying shrinkage of the specimens because the procedures do not allow exposure to more than one drying face.

Despite its being called “Specification for Packaged Dry, Hydraulic-Cement Grout (Non-Shrink),” there is no requirement in the specification for three very important properties of a high quality keyway grout: maximum allowable shrinkage; minimum bond strength; and the requirement for minimum strength of 6000 psi (41.4 MPa), as mentioned previously.

2. Requirements for free flowing can be attained with the fluid or flowable consistency classes cited in ASTM C 1107.

3. All cementitious materials should be protected from temperatures below 40°F (4.4°C). At these temperatures, hydration is impeded, adversely affecting strength and expansion development of non-shrink grouts. At temperatures slightly below 32°F (0°C), ice is formed, rendering the bond of the grout to the keyway ineffective whenever freezable moisture is present.

4. Polymer modified materials are preferred over cementitious products because of the following advantages:⁹
 - Improved bond to a substrate
 - Reduced chloride permeability
 - Internal self curing after initial moist curing
 - Improved freeze-thaw durability without air entrainment

Table 1. Non-shrink grout specification requirements: ASTM C 1107.

Compressive strength requirements:
– Restrained 2 in. (50.8 mm) cubes: ASTM C 942
Vertical height change requirements:
– Prehardening: ASTM C 827
– Post hardening: ASTM C 1090
Consistency requirements:
– Plastic and flowable: ASTM C 109
– Fluid: ASTM C 939

Note: ASTM C 1107 has no requirement for maximum shrinkage or minimum bond strength.

Table 2. Non-shrink grout compressive strength requirements: ASTM C 1107.

Keyway grout: component testing		
Age	Compressive strength requirements: restrained 2 in. (50.8 mm) cubes*	
	psi (min.)	MPa (min.)
1 day	1000 [†]	6.9
3 days	2500	17.2
7 days	3500	24.2
28 days	5000	34.5

* ASTM C 1107 has no requirement for minimum bond strength.

[†] Optional strength at 1 day.

- Lower creep coefficients

Note that a significant reduction in drying shrinkage is not an advantage in polymer modified portland cement mortars.

5. ASTM C 1107 does not differentiate between the type of aggregate non-shrink grouts. Non-metallic and metallic versions are produced by several manufacturers who are compelled to produce a grout meeting the same requirements of Table 1 of that specification regardless of the type of aggregate used.

Table 3. Non-shrink grout workability requirements: ASTM C 1107 specification consistency options.

Consistency options: ASTM C 939 flow cone or ASTM C 109 flow table			
Flow classification ASTM test method	Plastic C 109	Flowable C 109	Fluid C 939
Plastic and flowable			
Maximum at 5 drops	125 percent	<150 percent	n/a
Minimum at 5 drops	100 percent	>125 percent	n/a
Fluid			
Maximum, seconds	n/a	n/a	30
Minimum, seconds	n/a	n/a	10

Table 4. Non-shrink grout expansion requirements: ASTM C 1107 specification.

Expansion requirements: 3 x 6 in. (7.6 x 15.2 cm) vertical height change cylinders			
Grade classification Volume control type ASTM test method	-A- Prehardening C 827	-B- Post hardening C 1090	-C- Combination Both
Early height change			
Maximum percent at final set	+4.0	n/a	+4.0
Minimum percent at final set	-0.0	n/a	-0.0
Height change of moist cured hardened grout at 1, 3, 7, 14, and 28 days			
Maximum percent	n/a	+0.3	+0.3
Minimum percent	-0.0	-0.0	-0.0

Note: ASTM C 1107 gives no requirement for maximum shrinkage.

Table 5. Keyway component: Ohio DOT precast concrete bridge member testing.

Ohio DOT precast concrete mix design	Values	
Medusa Type III cement	650 lbs	295 kg
Drummond Island limestone	2000 lbs	907 kg
Hugo sand	1300 lbs	590 kg
Total water content	270 lbs	12.2 kg
Corrosion inhibitor	4 gal/cu yd	15 liters
Air content	5.0 percent	
Slump (water-cement ratio at 0.42)	5.5 in.	14 cm
Compressive strength [3 x 6 in. (7.6 x 15.2 cm) cylinders]	7225 psi	49.8 MPa

Table 6. Keyway component results: non-shrink grout, ASTM C 1107 compliance.

Mix design	Values			
Set non-shrink grout (Lot 24-9374-V4), lbs	50			
Mix water (0.8 gal or 13.5 percent), lbs	6.7			
Percent flow at 5 drops, ASTM C 230	128 at initial	56 at 15 mins.		
Vicat set time, (hr:min) ASTM C 807	4:40 at initial	6:15 at final		
Compressive strength, ASTM C 942 cubes, psi	1 day	3 days	7 days	28 days
Freshly mixed grout	4600	5870	6740	7360
After 30 mins. working time	4670	6390	7230	8052
Height change, ASTM C 1090 (3 x 6 in. cylinders)	1 day	3 days	14 days	28 days
Freshly mixed grout, percent	—	+0.02	+0.02	+0.03
After 30 mins., percent	—	+0.02	+0.02	+0.02

Note: 1 lb = 0.4536 kg; 1 gal = 3.785 liters; 1 psi = 0.006895 MPa; 1 in. = 2.54 cm.

6. Non-shrink grouts that have a minimum strength exceeding 6000 psi (41.4 MPa) may be selected for keyway grouting. Even though a 6000 psi (41.4 MPa) grout approaches the typical strength of the precast concrete member, the compressive strength of the grout is reported by 2 in. (50.8 mm) restrained cube specimens while

the precast concrete member is reported in ASTM C 39 cylindrical specimens.¹⁰ An adjustment must be made for converting cube strength to cylinder strength, and typically a strength reduction factor ranging from 0.80 to 0.75 is used to adjust 2 in. (50.8 mm) cubes to equivalent cylinder strength.

7. As indicated above, there is no bond strength requirement for non-shrink grouts cited in ASTM C 1107. Therefore, it is not possible to confirm completely whether a substrate concrete failure has occurred with this test alone.

TYPE OF SPECIMENS: COMPONENT AND COMPOSITE TESTING

Most grouts are specified using a property type specification. The Table 1 requirements of ASTM C 1107 are an example of the this type of component property approach. The grout, one part of the keyway assembly, must meet these minimum properties.

For the other part of the assembly — the precast concrete element — there may also be minimum properties. Requirements are often cited for compressive strength, water-cement ratio, air content, slump, unit weight, and elastic modulus for the precast concrete element.

This approach only addresses half of the problem. There is still no way to determine if the requirement for 100 percent substrate failure can be attained, unless the assembly is tested as a composite unit. The substrate concrete, often with unique properties, exposure conditions, and surface texture, must be tested with the grout to confirm the failure mode.

Laboratory Results: Component Testing

Because of the simultaneous requests from the two regional PCI associations, laboratory tests were conducted comparing two different grouting materials. Tests were run on component materials and structural composite assemblies.

Test results of the concrete used to produce the keyway shaped precast concrete elements of the assemblies are shown in Table 5. The concrete met the requirements of the local DOT specifications.

Two different grouting materials were used to compare the performance in both component and composite testing. The non-shrink grout, approved by many DOTs, attained the properties

Table 7. Keyway component: shear key non-shrink grout testing.

Mix design	Values	
Set non-shrink grout (Lot 24-9374-V1)	50 lbs	22.7 kg
Mix water [1 gal (3.7 liters) or 16.7 percent]	8.33 lbs	3.8 kg
7-day compressive strength (ASTM C 942)	5870 psi	40.5 MPa
7-day tensile strength (ASTM C 190)	390 psi	2.7 MPa

Table 8. Keyway component: shear keyway grout (Mg-NH₄-PO₄ mortar) testing.

Mix design	Values	
Set-45 hot weather (Lot 24-1605-T3)	50 lbs	22.7 kg
Mix water [0.47 gal (1.77 liters) or 7.8 percent by weight]	3.9 lbs	1.8 kg
7-day compressive strength (ASTM C 109)	7260 psi	50 MPa
7-day tensile strength (ASTM C 190)	557 psi	3.8 MPa
7-day flexural strength (ASTM C 348)	1128 psi	7.8 MPa

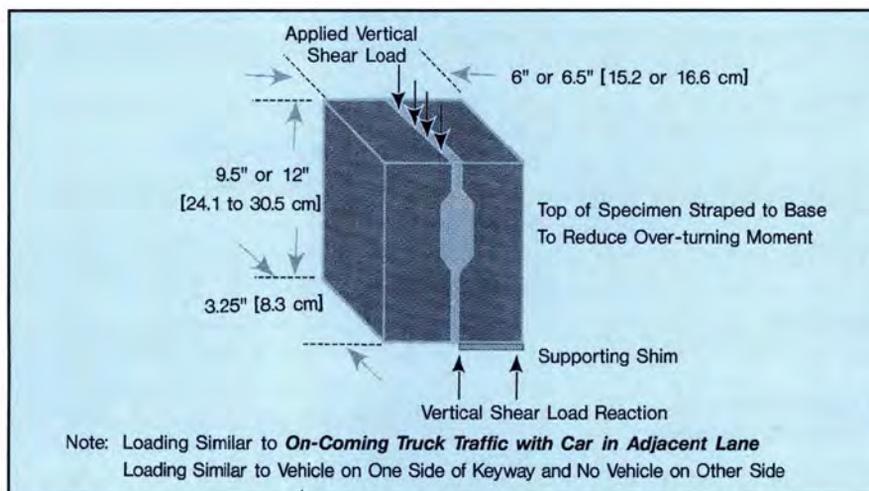


Fig. 6. Typical precast concrete box beam grouted keyway: direct vertical composite shear test.

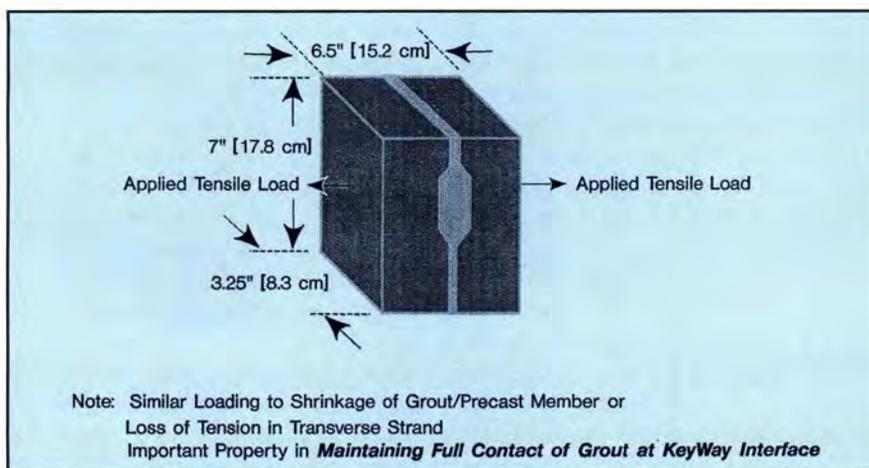


Fig. 7. Typical precast concrete box beam grouted keyway: composite direct tension test.

listed in Table 6. These values exceed the requirements in ASTM C 1107 Table 1.

For this particular test program, a bag of grout was sampled for the component and composite assembly testing. Grout properties at the time of testing are shown in Table 7. It can be seen that the 2 in. (50.8 mm) restrained cube compressive strengths met the requested minimum requirements of 6000 psi (41.4 MPa).

An alternative keyway grouting material was selected that had been used on several precast, prestressed concrete bridge projects in the northwest United States. It was also used on several Alaska precast concrete composite bridges on the Dalton Highway and the Moore Creek cable-stayed bridge near Skagway. The objective was to note any differences in performance in both component and composite assembly testing.

The material is a magnesium ammonium phosphate [Mg-NH₄-PO₄] mortar studied by Popovics.^{11,12,13} The retarded version was used because it has greater fluidity and has lower heat generation than the regular formulation that is typically used in rapid repairs of bridge decks and pavements. The product has been approved by many DOTs in the United States and Canada.

The material properties exceeded the 6000 psi (41.4 MPa) strength requirements, per ASTM C 109,¹⁴ and are cited in Table 8. The 2 in. (50.8 mm) cube air cured compressive strengths of this alternate material were about 25 percent higher than the non-shrink grout at the time of testing, despite being the retarded version of this product. The water demand of the product was about 50 percent lower than the non-shrink grout for about equal degrees of workability.

Composite Testing: A Different Approach

It was decided to test the component material in composite assemblies using several different types of tests. Each test was composed of two duplicate specimens. Four test series were evaluated.

The units were tested in vertical shear mode (see Fig. 6) to simulate the

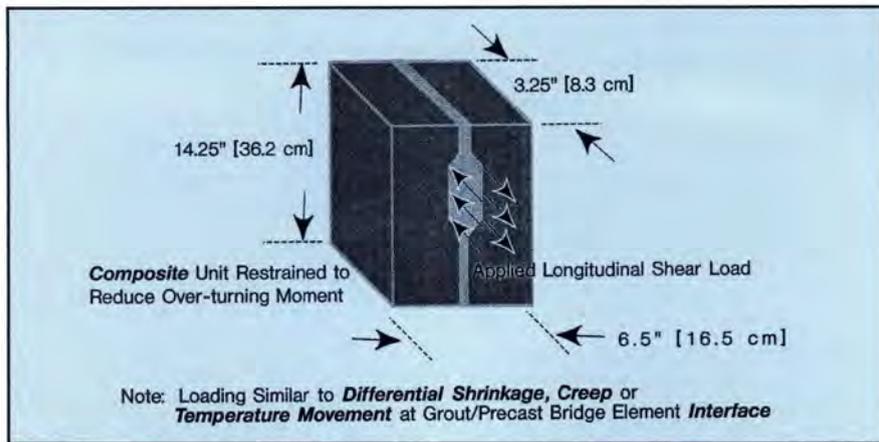


Fig. 8. Typical precast concrete box beam grouted keyway: composite direct longitudinal shear test.



Fig. 9. Consolidation of grout for composite units.

action of a vehicle wheel load on one member and no wheel load on the adjacent member. In a situation where there is a car in one lane and a truck in an adjacent lane, a similar differential loading pattern develops. Two sizes of specimen were cast: 8 and 12 in. (203 and 305 mm) shear keyway assemblies conforming to local DOT shape requirements.

To evaluate achievement of the 100 percent substrate failure requirement, the specimens were tested in direct tension (see Fig. 7). This direct tension test attempts to simulate the transverse shortening of the precast concrete member due to continual creep and shrinkage and also simulates the drying shrinkage that can occur in the keyway grout. Only one size speci-

men, the 8 in. (203 mm) deep keyway, was tested.

Precast, prestressed concrete members experience continuous creep from the prestressing force and shrinkage from the concrete. Longitudinal shear tests were performed (see Fig. 8) in the direction parallel to the keyway to simulate the action of the prestressed concrete member shortening due to creep and shrinkage while the grout does not shorten to the same degree. Only the 12 in. (305 mm) size composite specimens were used in this type of test.

Preparation and Curing Conditions

A total of 16 keyway assembly specimens were cast. All specimens were sandblasted to remove laitance and reveal coarse and fine aggregate tips in order to produce a bondable surface. All the dust of the fracture was flushed off the interior faces of the keyway prior to grouting with both types of material. In keeping with accepted practice for grouting, the keyway vertical surface was kept moist with damp towels for the non-shrink grouted assemblies to satisfy the initial concrete absorption.

A wooden form was used to dam the ends and the specimens were then filled with either the non-shrink grout or the $Mg-NH_4-PO_4$ mortar. A puddling stick was used to consolidate the grout in each specimen (see Fig. 9). No intentional surface saturation was provided for the $Mg-NH_4-PO_4$ mortar specimens except for water flushing to

remove the dust of the fracture after sandblasting the vertical faces.

Two specimens were cast for each type of grouting material. Only the vertical shear test was performed on both the 8 and 12 in. (203 and 305 mm) specimens.

Special Comparative Exposure Condition

To provide a worst case scenario, the contact surface of one series of eight additional keyway assemblies was intentionally left exposed to the laboratory air for several days to develop a carbonated interface after sandblasting but prior to grouting. These carbonated assemblies were used for the $Mg-NH_4-PO_4$ specimens only. The same number of specimens and testing orientation were performed on these carbonated specimens. Two specimens each were given this type of exposure.

Interface Exposure Implication: $Mg-NH_4-PO_4$ Mortar Systems

Air contains carbon dioxide (CO_2) that will react over time with the liberated lime from the hydrating concrete and produce a carbonated surface. This reaction is very typical of all concretes that do not have a sealer applied and whose surfaces are exposed directly to air at certain temperatures and humidity ranges.¹⁵

Carbonation in concrete can be easily confirmed, usually with a phenolphthalein solution indicator or a 10 percent hydrochloric (HCl) acid solution. When phenolphthalein is dripped on a carbonated surface, it remains colorless. If it is dripped on a non-carbonated surface or on a freshly fractured face, it will turn pink or purple if the pH of the solution pore water is higher than 8.4. The HCl solution will exhibit an aggressive "fizzing" when dripped on a carbonated surface or a surface containing the dust of the fracture. No aggressive fizzing occurs on a non-carbonated surface.

As $Mg-NH_4-PO_4$ materials develop an initially low pH phase, approximately 4.5, they later become buffered during hydration and stabilize at a pH of 8.5. During this early hydration phase, the acid phase reacts with the

carbonated interface and produces a noticeable fizzing. The contact surface forms bubbles, reducing the bond contact area at the bond interface. This action is similar to dropping acid on concrete whose surface had been moist cured with either ponding, wet burlap, or plastic sheeting and left to dry when exposed to the air afterward, allowing the surface to carbonate.

Comparative Curing

After grouting, the non-shrink grouted composite members were wrapped in damp towels and plastic to provide for optimum moist curing. This procedure produces more complete hydration of the cementitious grout. This practice is recommended by the manufacturer but is rarely followed on bridge element grouting projects. At the end of a 7-day curing period, the composite assemblies were stripped and allowed to air dry prior to testing on the next day. Virtually no drying shrinkage occurred with these specimens.

Specimens that were grouted with Mg-NH₄-PO₄ mortar were given only an air cure exposure, as recommended by the manufacturer. This is typical of most curing conditions for grouts used for filling the keyway in actual field practice. The Mg-NH₄-PO₄ specimens were tested at the same age as the non-shrink grout composites. These grouted assemblies were allowed to undergo some drying shrinkage.

COMPARATIVE COMPOSITE RESULTS

Comparative test results of the non-carbonated composite samples are shown in Table 9. In all cases, the Mg-NH₄-PO₄ grouted composites displayed an exceptionally higher failure load than the non-shrink grout composite specimens. The results were a minimum of 250 percent higher than the similarly fabricated non-shrink grouted composites. This difference is far greater than the measured 2 in. (50.8 mm) cube compressive strength differences between the two component materials. The highest comparative difference, showing a 600 percent improvement in strength, occurred

Table 9. Comparative composite test results: non-shrink grout vs. Mg-NH₄-PO₄ mortar.

Type of test	Failure load, lbs		Percent increase vs. non-shrink grout
	Non-shrink grout	Set-45 hot weather	
12 in. keyway longitudinal shear	2400*	14,300†	596
12 in. keyway vertical shear	5850*	16,500†	282
8 in. keyway vertical shear	7850*	20,250†	258
8 in. keyway direct tension	1940*	5730†	295

Note: 1 lb = 0.4536 kg; 1 in. = 2.54 cm.

* Bond line failure.

† Base concrete through grout failure.

Table 10. Comparative composite test results: keyway grout type and interface exposure.

Type of test	Failure load, lbs		Percent increase vs. non-shrink grout (worst case)
	Non-shrink grout	Carbonated keyway face Set-45 hot weather	
12 in. keyway longitudinal shear	2400*	4570†	190
12 in. keyway vertical shear	5580*	8500†	152
8 in. keyway vertical shear	7850*	11,345†	145
8 in. keyway direct tension	1940*	4145†	214

Note: 1 lb = 0.4536 kg; 1 in. = 2.54 cm.

* Failure at contact face of keyway in bond.

† Some bond line failure and bubbles at contact face.

Table 11. Comparative composite test results: interface exposure effect.

Type of test	Failure load, lbs		Percent decrease due to CO ₂ exposure
	Carbonated keyway face Set-45 hot weather	Non-carbonated keyway face Set-45 hot weather	
12 in. keyway longitudinal shear	4570*	14,300†	68.0
12 in. keyway vertical shear	8500*	16,500†	48.5
8 in. keyway vertical shear	11,345*	20,250†	43.9
8 in. keyway direct tension	4145*	5730†	27.7

Note: 1 lb = 0.4536 kg; 1 in. = 2.54 cm.

* Some bond line failure and bubbles at contact face.

† Base concrete through grout failure.



Fig. 10. Comparative failure modes: direct tension composite test.



Fig. 11. Comparative failure modes: vertical shear composite tests.



Fig. 12. Comparative failure modes: longitudinal composite shear tests.

with the lateral shear test composites on the 12 in. (305 mm) deep keyway composites.

The carbonated interface specimens were similarly tested and the results are compared in Table 10. The Mg-NH₄-PO₄ composites, even with the carbonated interface, still produced higher failure loads than the non-shrink grout samples. A minimum 140 percent increase in composite strength performance was attained with these adversely exposed specimens. They even out-performed the non-shrink grout composite specimens that were given optimum moist curing.

The relative difference in surface exposure of the carbonated and non-carbonated surfaces of the keyways used in the Mg-NH₄-PO₄ specimens was evaluated. Effects of carbonation exposure are compared in Table 11. Results range from a high of 68 percent to only 28 percent reduction in performance. Despite this adverse exposure, all carbonated specimens in the Mg-NH₄-PO₄ series still exceeded the optimally cured non-shrink grout composites.

Failure Modes

Comparative failure modes showed 100 percent substrate failure in the direct tension test of the Mg-NH₄-PO₄ composite non-carbonated specimens in all cases. Failure of the non-shrink grout always occurred at the bond line. Fig. 10 shows the relative failure modes in direct tension. The Mg-NH₄-PO₄ specimens failed in the 7200 psi (49.7 MPa) precast concrete when tested in direct tension, fracturing the coarse aggregate.

When tested in vertical shear, the failure modes of the non-shrink grout also always occurred at the bond line. Fracture occurred partially in the grout and the precast concrete with the Mg-NH₄-PO₄ mortars. Comparative failure modes are shown in Fig. 11. Little effect of eccentricity of the applied load was noted.

Although the comparative longitudinal shear results typically showed the highest percentage increase, the fractures reported did not appear to produce an expected failure mode as cracking transverse to the vertical key-

way developed (see Fig. 12). When the specimens were loaded, the applied load was transmitted through a bar. This bar rested in part on the specimen and in part on the grouted keyway haunch surface (see Fig. 13). An erratic pattern in the fracture occurred in the precast concrete. Part of this load pattern probably resulted from the built-in eccentricity in the testing procedure and the long span length of the larger longitudinal shear keyway specimens.

PREVIOUS LABORATORY RESULTS

Previous unpublished laboratory testing confirms the excellent properties of Mg-NH₄-PO₄ mortars (see discussion below and especially Figs. 14 through 18). Test data on bond strength and comparative drying shrinkage were evaluated to see if this could be the reason for the improved composite testing result differences. Chloride solution absorption was also checked to see if the mortar will readily pass a chloride solution from the top of the keyway to the bottom through the grouted keyway itself.

Bond Tests: Direct Tensile and Slant/Shear

The excellent bond strengths observed were confirmed by previous direct tensile bond testing on cored specimens taken from 4500 psi (31.0 MPa) limestone concrete substrates overlaid with Mg-NH₄-PO₄ mortars. Both the regular and the retarded overlay formulations produced substrate fractures when tested in direct tension. The substrate concrete was properly prepared and the carbonated surface was removed by sandblasting and flushing with water.

Direct tensile strength results approached 10 percent of the compressive strength of the substrate concrete whenever proper preparation to remove the carbonated zone was employed. When the surfaces were intentionally allowed to carbonate after preparation, bond line failures at a significantly lower level were attained. Bond line failure occurred with both types of Mg-NH₄-PO₄ type overlays

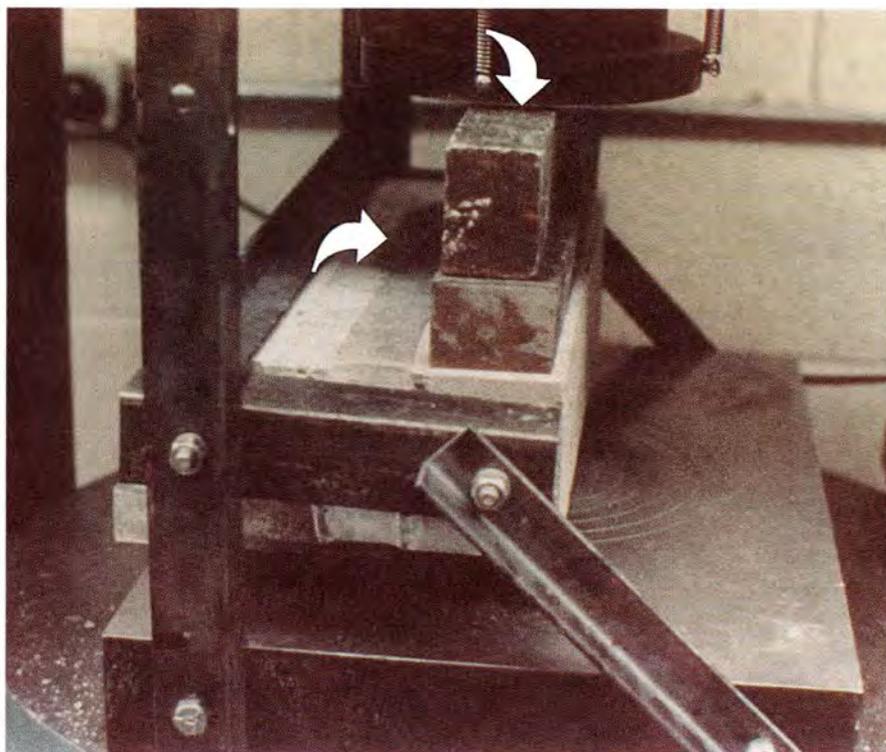


Fig. 13. Composite testing: longitudinal shear test orientation.

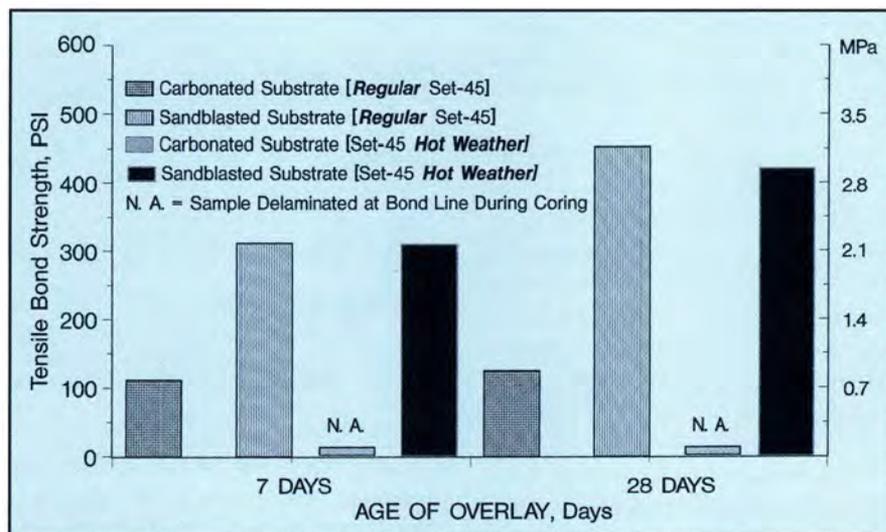


Fig. 14. Mg-NH₄-PO₄ comparative tensile bond strength: ACI 503 appendix method.

on carbonated surfaces (see Fig. 14).

When evaluated by ASTM C 882 slant/shear bond type testing on only 4300 psi [29.7 MPa] substrate concrete,¹⁶ Mg-NH₄-PO₄ overlays produced slant/shear bond test values, expressed on the elliptical surface area, meeting the requirement for epoxies covered under the ASTM C 881 specification¹⁷ (see Fig. 15). The effect of a carbonated surface readily produced lower slant/shear bond values that did

not provide results exceeding the minimum requirements of ASTM C 881 for epoxy concrete.

The bond of Mg-NH₄-PO₄ mortar to itself is quite remarkable as measured by this same test procedure. Because Mg-NH₄-PO₄ mortars are not susceptible to carbonation, due to the absence of lime in the system, the high bond of the material to itself is logical. This has implications for permitting grouting in horizontal lifts.

Because shear results can be influenced by relative differences in drying shrinkage of the grout compared to the precast concrete member, any grout with low drying shrinkage should produce higher shear test values as this additional shear stress is minimized. Note that this type of shrinkage is long term drying shrinkage and is not considered a vertical settlement shrinkage correction, which is mandatory for non-shrink grouts.

Shrinkage Tests: Length Change and Weight Change

Drying shrinkage values were compared using 3 x 3 x 10 in. (76.2 x 76.2 x 254 mm) ASTM C 157¹⁸ prisms, which allow exposure to 50 percent relative humidity on four sides at 70°F (21°C). The results show Mg-NH₄-PO₄ mortars shrink five times less than 0.32 water-cement ratio concretes having a 3/4 in. (19 mm) maximum size aggregate (see Fig. 16). Given identical conditions, an even greater difference would be anticipated with non-shrink grouts because no coarse aggregate restraining effect occurs in the non-shrink grout prisms.

The comparative drying shrinkage of Mg-NH₄-PO₄ systems was monitored using a 4 in. (102 mm) cube, weight change procedure similar to that found in NCHRP T 244 for evaluating sealers.¹⁹ After curing in a plastic bag, all of the cubes were allowed to air dry in a 70°F (21°C), 50 percent relative humidity environment for over 2 months. The Mg-NH₄-PO₄ specimens were cast with both 3/8 in. (9.5 mm) pea gravel and also as mortar only specimens, while the reference portland cement specimens were only cast with the 3/8 in. (9.5 mm) pea gravel aggregate. Confirmation of the Mg-NH₄-PO₄ mix's lower drying shrinkage rates, by weight loss, is shown in Fig. 17.

Chloride Absorption Confirmation

Chloride absorption was also monitored using 4 in. (102 mm) cube specimens. These data, shown in Fig. 18, compare portland cement mixes containing 3/8 in. (9.5 mm) pea gravel aggregate and 0.6 water-cement ratio by

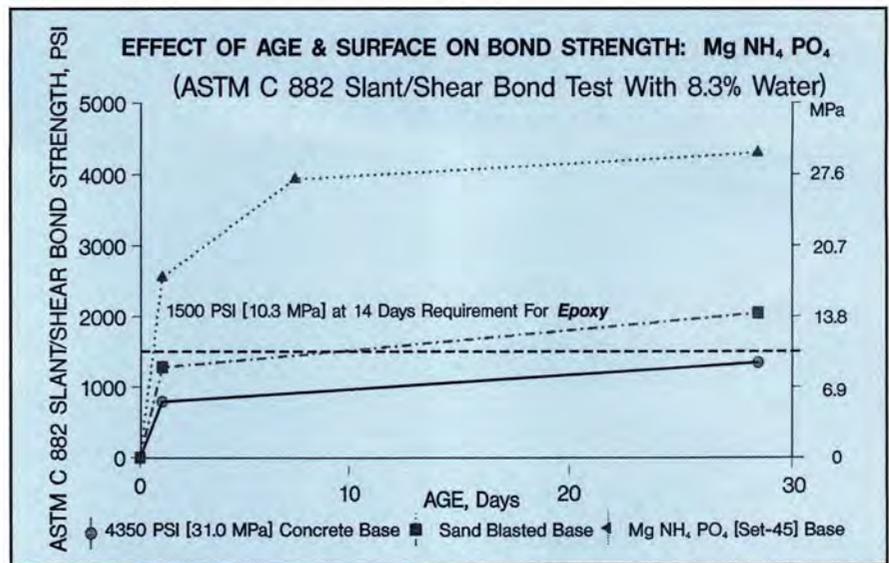


Fig. 15. Effect of age and surface condition on bond strength: Mg-NH₄-PO₄, ASTM C 882 method.

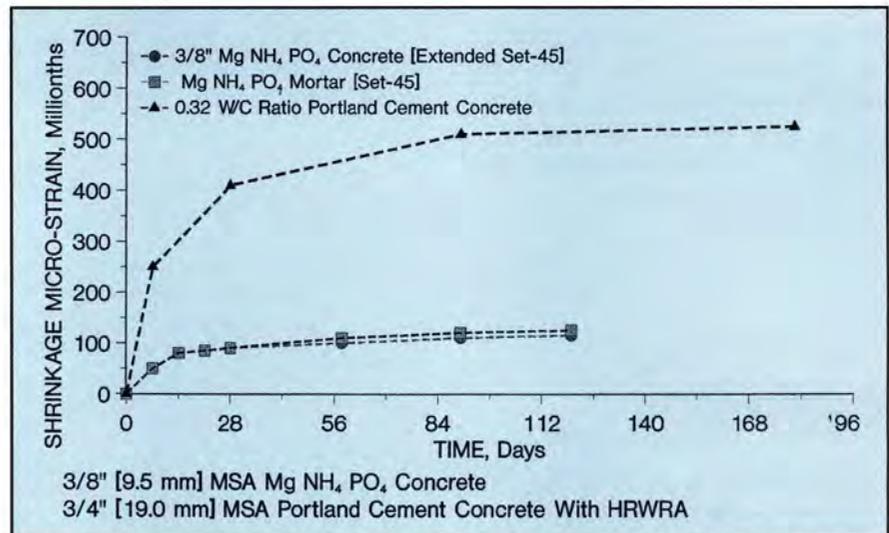


Fig. 16. Comparative Mg-NH₄-PO₄ vs. concrete shrinkage: ASTM C 157 method.

weight. Much less chloride solution uptake was observed with the Mg-NH₄-PO₄ than with the portland cement concrete specimens. These data confirm work done by Pfeifer.²⁰ The Mg-NH₄-PO₄ concrete mixes were compared to specialty concretes and structural concretes coated with silanes. Low chloride permeability was also noted in this other independent study.

CONCLUSIONS

1. Composite testing provides a method for evaluating the type of resulting fracture produced at ultimate strength of the specimens. Failure loads that produce failure in the substrate concrete are the maximum at-

tainable, unless the strength of the substrate concrete is modified.

2. Composite testing of grouted keyway assemblies provides much more practical information than component testing of the materials. Effects of grouting materials, precast concrete member keyway shapes, curing, substrate exposure, and texture can be evaluated.

3. Composite assemblies made with Mg-NH₄-PO₄ mortars have shown higher values when tested for direct tensile bond strength, vertical shear strength, and longitudinal shear strength — far greater than accounted for in the slight difference in compressive strength compared to non-shrink grout assemblies.

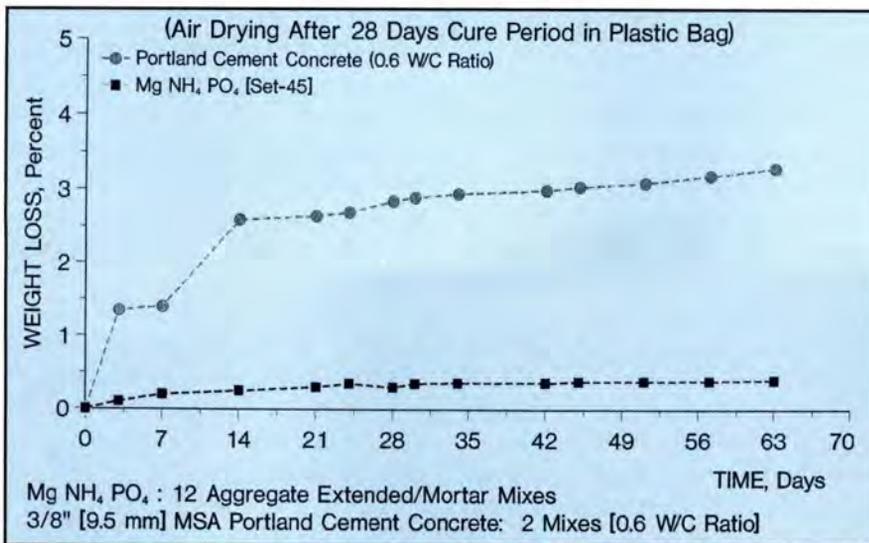


Fig. 17. NCHRP T-244 comparative 4 in. (102 mm) cube drying: Mg-NH₄-PO₄ and concrete weight change.

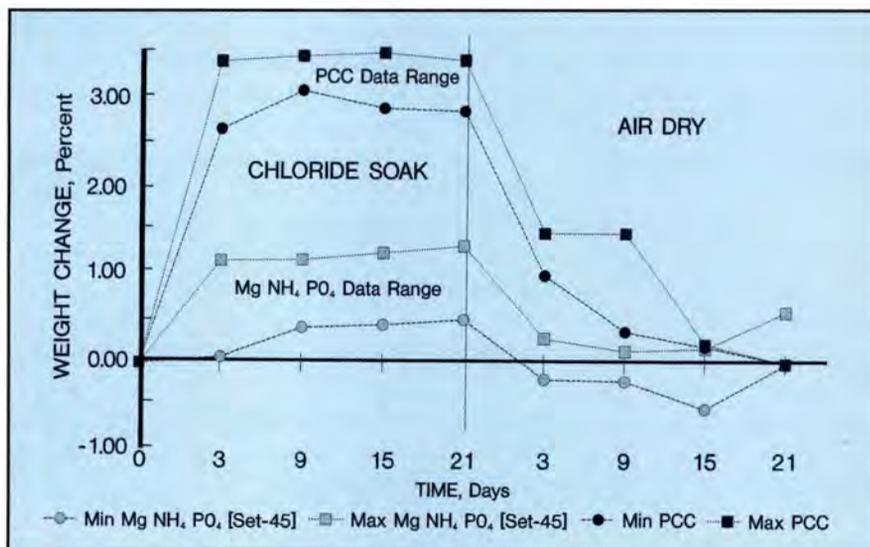


Fig. 18. NCHRP T-244 comparative weight change: 4 in. (102 mm) cube (chloride soak and air dry phase).

4. The remarkably good tensile bond test results compare favorably to the excellent bond strength properties of Mg-NH₄-PO₄ mortars. Of the materials tested, this material was the only one that met the 100 percent substrate failure criterion cited by the requesting regional PCI associations.

5. Despite purposely producing a less than optimum bondable carbonated surface, higher composite strengths were still attained with Mg-NH₄-PO₄ mortar specimens than with commonly used, but moist cured, non-shrink grouted specimens.

6. The effect of carbonation at the interface of the substrate concrete will produce lower bond strengths with

Mg-NH₄-PO₄ systems. This reduced bond effect can be negated by checking the surface for carbonation and with adequate, but timely, preparation prior to keyway grouting. Significant carbonation is less likely to occur on very low water-cement ratio, properly cured, and properly prepared concrete surfaces.

7. The drying shrinkage of Mg-NH₄-PO₄ mortars/concretes is significantly lower than 0.32 water-cement ratio concretes containing coarse aggregates. This difference occurs in both lower weight loss and lower length change values due to drying shrinkage. This may have important long term implications on the im-

proved vertical and lateral shear resistance of the Mg-NH₄-PO₄ grouted composite specimens. Compared to the moist cured non-shrink grout specimens, further comparative improvement in shear capacity may be experienced due to significantly lower drying shrinkage of Mg-NH₄-PO₄ systems.

8. Significantly lower chloride absorption of the Mg-NH₄-PO₄ materials occurs as confirmed in separate investigations. This is an important property for keyway grouts that can absorb and/or pass chlorides from road salts or sea sprays to the underside of precast, prestressed concrete box beams and bulb tees through the grout itself or along the failed bond interface.

RECOMMENDATIONS

Based on the findings in this paper resulting from field, laboratory, and other investigative sources, the following recommendations are offered for guidance in selecting a high performance keyway grout. This will eliminate the weak link in the keyway composite and eliminate inadequate specifications based on the component specification reliance. These recommendations will not substantially increase the cost of the grouted element nor will any major design changes or sophisticated details be required.

1. Preliminary consideration should be given to keyway grouting materials that have inherent bond strength high enough to fail in the substrate of properly prepared high strength concretes, preferably in an air curing environment. Materials that produce failure in the substrate concrete in direct tension, per ACI 503 Appendix Testing, and exceed the ASTM C 882 slant shear test for epoxy requirements may be initially considered.

2. Further screening should be given to materials that have very low negative shortening strains based on the ASTM C 157 length change test. Care should be taken to measure shrinkage strains from the point of maximum expansion if the material complies with the mandatory vertical height change requirements of ASTM C 1107, Table 1. A good check on shrinkage without involving net shrinkage determinations [expansion

(minus) shrinkage] is to use weight change determinations. NCHRP T 244 offers a good basis to compare specialty concrete systems.

3. The same NCHRP T 244 report offers a method to select materials that display low chloride absorption capability without the necessity of using other more sophisticated testing procedures. The AASHTO 90-day modified ponding test may offer the same type of chloride screening.

4. Provide all keyway faces with an aggressive grit blasted texture at the plant immediately prior to shipment to the job site. The dust of fracture must be removed with pressure washing. A second option is grit blasting of faces, followed by high pressure washing, at the job site. These preparation methods will remove surface laitance and form release agents, both of which produce a substrate with poor bonding qualities. Such a procedure will produce a substrate interface with the tips of the coarse and fine aggregate exposed, while at the same time removing initial carbonation. In cases where the specimens are only grit blasted at the plant to produce adequate texture, a high pressure power washing of the surface is necessary to remove any road dirt and recent carbonation immediately prior to erection and grouting at the job site.

Adequacy of preparation can be ver-

ified by testing the prepared surface with a 10 percent HCl solution and comparing it to the top of the element, which has not been similarly prepared. Aggressive fizzing should be noted on the non-grit blasted (top) surface.

Similarly, a solution of phenolphthalein can be used as a comparative screening test, with a pink or purple color indicating a non-carbonated surface. Phenolphthalein will not be adversely affected by the fine dust of fracture that may remain if high power water flushing is not used. Because of the alkalis in portland cement, a slight pink hue may be noted on the carbonated surface. For this reason, both test methods should be used on a comparative basis.

5. Specify a direct tension procedure for a composite test evaluation (properly prepared keyway and keyway grouting material) to determine the failure mode and failure load. Best results are obtained with failure within the keyway substrate concrete.

6. Test the composite keyway in vertical shear to determine the failure mode and also the magnitude of failure load. This testing should be performed after the materials are given a proper curing period, as recommended by the manufacturer, and also after some drying shrinkage has occurred.

7. Mg-NH₄-PO₄ mortars show the above properties through laboratory

testing and have been successfully used in field applications for keyway grouting. Their continued use should be encouraged in this application to eliminate some of the keyway related problems encountered to date. Carbonation testing, as recommended above, will ensure optimum bond and shear capacity.

8. The use of non-shrink grouts should be discouraged for keyway grouting applications unless the specific proposed material passes the considerations provided in numbers 1, 2, 3, 5, and 6 above.

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REFERENCES

1. Huckelbridge, A., El-Esnawi, H., and Moses, F., "An Investigation of Load Transfer in Multi-Beam Prestressed Box Girder Bridges," Ohio Department of Transportation Report FHWA/OH-94/002, Department of Civil Engineering, Case Western Reserve University, Cleveland, OH, September 1993.
2. Whiting, D., and Stejskal, B. G., "Field Studies of Corrosion in Prestressed Concrete Bridges," Philip D. Cady International Symposium on Concrete Bridges in Aggressive Environments, ACI SP-151, R. E. Weyers, Editor, American Concrete Institute, Detroit, MI, pp. 73-93.
3. "Standard Specification for Packaged, Dry Hydraulic-Cement Grout (Nonshrink)," ASTM Designation C 1107, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
4. "Standard Test Method for Compressive Strength of Grouts for Preplaced-Aggregate Concrete in the Laboratory," ASTM Designation C 942, American Society for Testing and Materials, ASTM Standards Volume 04.01, Philadelphia, PA, 1993.
5. "Standard Specification for Flow Table for Use in Tests of Hydraulic Cement," ASTM Designation C 230, American Society for Testing and Materials, ASTM Standards Volume 04.01, Philadelphia, PA, 1993.
6. "Standard Test Method for Flow for Preplaced-Aggregate Concrete (Flow Cone Method)," ASTM Designation C 939, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
7. "Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens from Cementitious Mixtures," ASTM Designation C 827, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
8. "Standard Test Method for Measuring Changes in Height of Cylindrical Specimens from Hydraulic-Cement Grout," ASTM Designation C 1090, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
9. ACI 548.3R-91, "State-of-the Art on Polymer Modified Concrete," *Manual of Concrete Practice*, Part 5, American Concrete Institute, Detroit, MI, 1991.
10. "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM Designation C 39, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
11. Popovics, S., Rajendran, N., and Penko, M., "Rapid Hardening Cements for Repair of Concrete," *ACI Materials Journal*, V. 84, No. 1, January-February 1987.
12. Popovics, S., and Rajendran, N., "Early Age Properties of Magnesium Phosphate-Based Cements Under Various Temperature Conditions," *Concrete and Concrete Construction*, Transportation Research Record 1110, Transportation Research Board, Washington, DC, 1987.
13. Popovics, S., and Rajendran, N., "Test Methods for Rapid Hardening Magnesium Phosphate-Based Cements," *Cement, Concrete and Aggregates*, American Society for Testing and Materials, V. 10, No. 1, Summer 1988.
14. "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)," ASTM Designation C 109, American Society for Testing and Materials, ASTM Standards Volume 04.01, Philadelphia, PA, 1993.
15. Verbeck, G., "Carbonation of Hydrated Portland Cement," Research Department Bulletin, RX087, Portland Cement Association, Skokie, IL, 1958.
16. "Standard Test Method for Bond Strength of Epoxy Resin Systems Used With Concrete by Slant Shear," ASTM Designation C 882, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
17. "Standard Specification for Epoxy-Resin Base Bonding Systems for Concrete," ASTM Designation C 881, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
18. "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," ASTM Designation C 157, American Society for Testing and Materials, ASTM Standards Volume 04.02, Philadelphia, PA, 1993.
19. Pfeifer, D., and Scali, M., "Concrete Sealers for Protection of Bridge Structures," National Cooperative Highway Research Program Report 244, Transportation Research Board, National Research Council, Washington, D.C., December 1981.
20. Pfeifer, D., "Corrosion Problems and Solutions for New and Old Parking Structures," *Parking Professional*, October 1984.